STUDY OF CHARGED HIGGS BOSONS SEARCH AT THE ILC FOR A COLLISION ENERGY OF 1 TEV

Presentation by Christian Drews

Academic advisors: Professor Hitoshi Yamamoto (Tohoku Uni.)
Professor Arno Straessner (TU Dresden)
Overview

• Full simulation study of ILC/ILD
• $m_{H^±} = 350$ GeV cross section = 9 fb $\text{BR}(H^± \rightarrow bt) = 90\%$
• $E^+e^- \rightarrow H^+H^- \rightarrow tb\ tb \rightarrow Wbb\ Wbb$ $\rightarrow 2\ \text{jets}$ 8 jets (hadronic)
• $Wbb\ Wbb \rightarrow 2\ \text{jets}$ 6 jets + lepton (semi-lep.)
• Major background:
  • $ttH/ttZ/ttg \rightarrow ttbb$
  • $tt \rightarrow bWbW$
  • HA $\rightarrow bbbb$ (SUSY)
  • H/A $\rightarrow tt$ at resonance
  • Ignoring SUSY background
• Goal: $m_{H^±}$ measurement
  • Samples with 340, 346, 348, 350, 352, 354, 360 GeV mass
Cross section

- $\sigma \approx 9$ fb with $P = (-80\%, 20\%) 10.4$ fb
- $\mathcal{L} = 1000$ 1/fb
- Hadronic: 5100 events
- Semileptonic: 3200 events

Allowed parameter space


Beam background reduction with kt-Algorithm

Reconstructed $H^+$ and $H^-$ mass with realistic clustering and pairing with generator information

$R$ chosen to be 1.3
Jet pairing

- Jet pairing with chi squared minimization
  - $j_1, j_2, j_3$ and $j_4$ – jets with highest b-tag
  - For semi-leptonic: $j_7$ and $j_8$ are neutrino and lepton

\[ \chi^2 = \left| \frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma_{H+}^2} \right| + \left( \frac{m_{j_2j_3j_4} - M_t}{\sigma_t} \right)^2 + \left( \frac{m_{j_6j_7j_8} - M_t}{\sigma_t} \right)^2 + \left( \frac{m_{j_3j_4} - M_W}{\sigma_W} \right)^2 + \left( \frac{m_{j_7j_8} - M_W}{\sigma_W} \right)^2 \]

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Mid: the 4 b-jets have highest b-tag in the event

For every color singlet there are 2 jets with a major fraction from this singlet

Jet pairing agrees with major color singlet fraction in jet
Neutrino four momentum

- Missing-Energy-Method (MEM)
  \[ p_{\text{vis}} = \sum_{i=1}^{N_{\text{PFO}}} p_i \]
  \[ p_{\text{CMS}} = (1000, 0, 0, 1000 \cdot \sin(0.014/2)) \]
  \[ p_{\nu,\text{MEM}} = (p_{\text{CMS}} - p_{\text{vis}}) \]

- Standard for most studies

- Missing-Direction-Method (MDM)
  - Using the Direction of Missing-Energy-Method and calculation the Energy by fixing W-Mass

\[ E_{\nu,\text{NDM}} = \frac{m_W^2}{E_l(1 - \alpha)} \]
\[ \alpha = \frac{\vec{p}_{\nu,\text{MEM}} \cdot \vec{p}_l}{|\vec{p}_{\nu,\text{MEM}}| |\vec{p}_l|} \]
\[ p_{\nu,\text{NDM}} = (E_{\nu,\text{NDM}}, E_{\nu,\text{NDM}} \frac{\vec{p}_{\nu,\text{MEM}}}{|\vec{p}_{\nu,\text{MEM}}|}) \]
Neutrino four momentum

- Missing Momentum Method (MMM)
  - Using momentum form MEM for energy estimation
    \[ p_{\nu,\text{MMM}} = (|\vec{p}_{\nu,\text{MEM}}|, \vec{p}_{\nu,\text{MEM}}) \]

- Missing Transversal Momentum Method (MTMM)
  - Using only the momentum in transversal momentum
    \[ \frac{m_W^2}{2} = E_\nu E_\ell - \vec{p}_\nu \vec{p}_\ell = E_\ell \sqrt{p_{\nu x}^2 + p_{\nu y}^2 + p_{\nu z}^2 - p_{\nu x} p_{\ell x} - p_{\nu y} p_{\ell y} - p_{\nu z} p_{\ell z}} \]

has two solutions

\[ p_{\nu z} = \frac{\pm K + p_{\ell z} [2(p_{\ell y}p_{\nu y} + p_{\ell x}p_{\nu x}) + m_W^2]}{2(p_{\ell x} + p_{\ell y})} \]

\[ K = E_\ell \sqrt{4[(2p_{\ell x}p_{\nu x} + m_W^2)p_{\ell y}p_{\nu y} - p_{\ell x}^2 p_{\nu y}^2 - p_{\ell y}^2 p_{\nu x}^2 + m_W^2 p_{\ell x} p_{\ell y}]} + m_W^4} \]
Neutrino reconstruction

Neutrino energy

Neutrino momentum in z-direction

MTMM | Transversal momentum
MDM | Direction
MEM | Standard with missing energy
MMM | Only using momentum

MTMM | Transversal momentum
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MEM | Standard with missing energy
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Event selection

- Different event selections were used
  - Static cuts
  - BDT

- Optimizations
  - Signal significance
  - Significance for correctly paired signal (BDT + separate BDTG)

<table>
<thead>
<tr>
<th>Cut type</th>
<th>Optim. type</th>
<th>Mode</th>
<th>Sig</th>
<th>o. Sig</th>
<th>Z(h)</th>
<th>t\bar{t}Z</th>
<th>t\bar{b}b</th>
<th>t\bar{t}(sl)</th>
<th>t\bar{t}(h)</th>
<th>t\bar{t}h(sl)</th>
<th>t\bar{t}h(h)</th>
<th>other</th>
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<tr>
<td>Static cuts</td>
<td>(h)</td>
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<td>138</td>
<td>106</td>
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<tr>
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<td>26</td>
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<tr>
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<td>corr. paired</td>
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<td>50</td>
<td>61</td>
<td>112</td>
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<td>103</td>
<td>4</td>
<td>0</td>
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<tr>
<td>Static cuts</td>
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<td>(sl)</td>
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<td>1154</td>
<td>0</td>
<td>46</td>
<td>54</td>
<td>12</td>
<td>122</td>
<td>12</td>
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<tr>
<td>BDT</td>
<td>(h)</td>
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<td>2156</td>
<td>59</td>
<td>0</td>
<td>136</td>
<td>104</td>
<td>363</td>
<td>12</td>
<td>206</td>
<td>18</td>
<td>5</td>
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<tr>
<td>BDT</td>
<td>(sl)</td>
<td></td>
<td>3495</td>
<td>519</td>
<td>139</td>
<td>215</td>
<td>161</td>
<td>59</td>
<td>640</td>
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<td>373</td>
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<td>27</td>
<td>65</td>
<td>2</td>
<td>54</td>
<td>2</td>
<td>0</td>
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<tr>
<td>BDT</td>
<td>corr. paired</td>
<td>(sl)</td>
<td>865</td>
<td>936</td>
<td>0</td>
<td>18</td>
<td>30</td>
<td>5</td>
<td>63</td>
<td>4</td>
<td>69</td>
<td>0</td>
</tr>
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</table>

Table 2.10: Remaining background after the event selections; (h) stands for hadronic and (sl) stands for semi-leptonic
Mass measurement

- Template method
  - Compare mass distribution shape -> calculation $\chi^2$
  - Get uncertainty from $\chi^2$ parabola
- Shape method
  - Get shape of BG, correctly paired signal and false paired signal
  - Calibrate fitted mean to Higgs mass
- Combined method
  - Reduce fitting variables to Higgs mass from cor. and false paired signal
Study of charged Higgs bosons search at the ILC for a collision energy of 1 TeV

Template method

\[ \chi^2 = \sum_{i=0}^{N} \frac{T_i - S_i}{\sqrt{S_i}} \]

\( \chi^2 / \text{ndf} = 1.311 / 4 \)

Prob = 0.8596

p0 = 2.994e+05 ± 1.396e+04

p1 = -1706 ± 79.79

p2 = 2.429 ± 0.114
Shape method

• Get signal shape (Static Cuts)

Correctly paired signal

Failed clustering

Total signal

Static cuts

\[ N_s \text{ (exp.)} = 5491 \]

Correctly paired: (24.5%):

\[ \mu_s: 352.1 \text{ GeV} \]

\[ \sigma_L: 24.8 \text{ GeV} \]

\[ \sigma_R: 12.8 \text{ GeV} \]

Wrong paired (75.5%):

\[ \mu_s: 355.1 \text{ GeV} \]

\[ \sigma_L: 45.6 \text{ GeV} \]

\[ \sigma_R: 71.5 \text{ GeV} \]

\[ \text{red. } \chi^2 = 2.05 \]
Shape method

- Get background shape (Static Cuts)

**Static cuts**

\[ N_B \text{ (exp.)} = 2418 \]
\[ \mu = 373.8 \text{ GeV} \]
\[ \sigma_L = 69.2 \text{ GeV} \]
\[ \sigma_R = 74.8 \text{ GeV} \]

red. \[ \chi^2 \text{ (original BG) } = 3.06 \]
red. \[ \chi^2 \text{ (gen BG) } = 0.96 \]
Added fit

• Added fit for different event selections for shape method

• All fit parameter fixed except mean of signal distributions

• Background
• Signal (solid)
  • Wrong paired signal (dashed)
  • Correctly paired signal
Shape method – mass estimation (BDT – correctly paired)

- Linear regression for signal distribution maximum and generated mass
- Test data set (blue)

Linear regression for corre. paired signal

\[ \chi^2 / \text{ndf} = 1.369 / 5 \]

Prob: 0.9277

| p0 | \(-0.03791 \pm 0.2589\) |
| p1 | \(1.054 \pm 0.04322\) |

Linear regression for wrong paired signal

\[ \chi^2 / \text{ndf} = 0.5786 / 5 \]

Prob: 0.989

| p0 | \(0.3524 \pm 0.5018\) |
| p1 | \(0.08468 \pm 0.5363\) |

BDT correctly paired

\[ m_{c,H}/\text{GeV} = 349.74 \pm 0.68 \text{ (Corr. pairing)} \]
\[ m_{w,H}/\text{GeV} = 350.16 \pm 2.59 \text{ (Wrong pairing)} \]
\[ m_{a,H}/\text{GeV} = 349.83 \pm 0.46 \text{ (combined)} \]
\[ m_{r,H}/\text{GeV} = 349.77 \pm 0.66 \text{ (combined)} \]

\[ \Delta_{c,\text{const}} = 0.2456 \]
\[ \Delta_{c,\text{linear}} = -0.012 \]
\[ \Delta_{c,\text{fit}} = 0.6319 \]

\[ m_{c,H}/\text{GeV} = (1.05 \pm 0.04) \mu_c + (352.1 \pm 0.26) \]
\[ m_{w,H}/\text{GeV} = (0.54 \pm 0.08) \mu_w + (339.09 \pm 0.5) \]
MC toy with varied cross section (BDT – correctly paired)

- Result from 10 000 toy MC
MC toy with varied cross section (BDT – correctly paired)

- Result from 10,000 toy MC samples
- 0.5 GeV mass precision
- Optimization for correctly paired signal beneficial

Mass uncertainty with reduced shape method
Result

- 0.5 GeV mass precision
- Neutrino four momentum reconstruction with Missing Momentum Method was used
- Missing Transversal Momentum Method has great potential

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<tr>
<th>Cut type</th>
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<th>Mode</th>
<th>Signif.</th>
<th>Signif.</th>
<th>Effi.</th>
<th>Purity</th>
<th>mass precision with $\sigma = 9$ fb</th>
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<tbody>
<tr>
<td>Static cuts</td>
<td>hadronic</td>
<td>44.6</td>
<td>17.9</td>
<td>65 %</td>
<td>64 %</td>
<td></td>
<td>0.56 GeV</td>
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<td>Static cuts</td>
<td>semi-lep.</td>
<td>36.5</td>
<td>17.3</td>
<td>43 %</td>
<td>67 %</td>
<td></td>
<td></td>
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<tr>
<td>Static cuts corr. paired</td>
<td>hadronic</td>
<td>37.2</td>
<td>21.9</td>
<td>62 %</td>
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<td></td>
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Backup
Cross section

- $\sigma \approx 9 \text{ fb with } P = (-80\%, 20\%) \quad 10.4 \text{ fb}$
- $\mathcal{L} = 1000 \text{ 1/fb}$
- $N = 10400 \text{ } H^\pm \text{ events}$
- Assuming $\text{BR}(H^\pm \rightarrow tb) = 90\%$
- $\text{BR}(t \rightarrow bW) = 100\%$
- $\text{BR}(W \rightarrow 2\text{jets}) = 67.6\%$
- $\text{BR}(W \rightarrow ev) = 10.75$
- $\text{BR}(W \rightarrow ev) = 10.57$
- Hadronic: 5100 events
- Semileptonic: 3200 events

Source: *Charged Higgs Boson production at ee colliders in the complex MSSM: a full one-loop analysis*
Allowed parameter space

<table>
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<tr>
<th>Type</th>
<th>$U_R$</th>
<th>$D_R$</th>
<th>$L_R$</th>
<th>$\lambda_{UU}$</th>
<th>$\lambda_{DD}$</th>
<th>$\lambda_{LL}$</th>
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<tbody>
<tr>
<td>I</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>$\cot \beta$</td>
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<td>II</td>
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<td>-</td>
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<td>$- \tan \beta$</td>
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Table 1. Assignment of $Z_2$ charges for the right-handed fermions, and the resulting relations among Yukawa coupling matrices in the $Z_2$-symmetric types of 2HDM Yukawa sectors. The Higgs doublets $\Phi_1$ and $\Phi_2$ have $Z_2$ quantum numbers $-$ and $+$, respectively.

Analysis Overview

• Isolated Lepton selection
• Reduce beam background by \(kt\)-Algorithm
• Jet-clustering and flavor tagging (LCFIplus)
• Calculating neutrino four-momentum (only semi-leptonic)
• Jet-pairing
• Extracting signal and background mass shape
• Added fit to find Higgs-mass
Find R for kt-Algorithm

Reconstructed $H^+$ and $H^-$ mass with realistic clustering and pairing with generator information
### Chi² - Jet Pairing (hadronic)

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- **Chi²** expression:

\[
\chi^2 = \left| \frac{(m_{j_1j_2j_3j_4})^2 - (m_{j_5j_6j_7j_8})^2}{2\sigma_H^2} \right| + \left( \frac{m_{j_2j_3j_4} - M_t}{\sigma_t} \right)^2

+ \left( \frac{m_{j_6j_7j_8} - M_t}{\sigma_t} \right)^2

+ \left( \frac{m_{j_3j_4} - M_W}{\sigma_W} \right)^2

+ \left( \frac{m_{j_7j_8} - M_W}{\sigma_W} \right)^2
\]

- the 4 b-jets have highest b-tag in the event
- For every color singlet there are 2 jets with a major fraction from this singlet
- Jet pairing agrees with major color singlet fraction in jet
Lepton Selection

- Using the IsolatedLeptonTaggingProcessor
  - From MarilnReco
  - Based on MVA
- Open task: reduce false Lepton Tag in hadronic Channel
  - With event shape or b-tag
  - But actually the pairing efficiency is not effected

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<tr>
<th></th>
<th>Total (%)</th>
<th>w/o tau (%)</th>
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<tbody>
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<td>Correct Tag</td>
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<td>False Lepton Tagged</td>
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<td>Electron</td>
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<td>89.4 (w/o tau and myon)</td>
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<tr>
<td>Myon</td>
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<tr>
<td>False Lepton Tag in hadronic</td>
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